Journal of Plant Nutrition
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713597277

Interrelationships between growth and nutrient uptake in alfalfa and corn

V. C. Baligar[a,b]
[a] Department of Land Resource Science, University of Guelph, Ontario, Canada [b] USDA-ARS, Appalachian Soil and Water Conservation Research Laboratory, Beckley, WV

To cite this Article Baligar, V. C.(1986) 'Interrelationships between growth and nutrient uptake in alfalfa and corn', Journal of Plant Nutrition, 9: 11, 1391 — 1404
To link to this Article: DOI: 10.1080/01904168609363536
URL: http://dx.doi.org/10.1080/01904168609363536

JOURNAL OF PLANT NUTRITION, 9(11), 1391-1404 (1986)

INTERRELATIONSHIPS BETWEEN GROWTH AND NUTRIENT UPTAKE IN ALFALFA AND CORN

KEY WORDS: Root and shoot growth rates, net influx rates, N, P, K, Na, Ca, Mg.

V. C. Baligar[1]

Department of Land Resource Science
University of Guelph, Ontario, Canada N1G 2W1

ABSTRACT

Nutrient requirements of plants during their various phases of growth are affected by several internal and external factors. The changes in rate of uptake by root with age are an important factor to meet the increasing plant demand for nutrients. Nutrient culture experiments were carried out under controlled greenhouse conditions with corn (Zea Mays L.) and alfalfa (Medicago sativa L.) to investigate the relationship of stage of growth to changes in plant parameters and nutrient uptake properties. With advancement of age, both plant species increased their ambient growth medium pH towards neutrality. With increasing age in alfalfa there was very little change in observed S:R ratio and root growth rate. On the other hand in corn plants the S:R ratio increased and growth rate for root and shoot decreased with age. Alfalfa contained higher concentrations of N, K, Na, and Ca than corn; while ion concentrations in both crops decreased with plant age. At all stages of growth, alfalfa absorbed less nutrients than corn. The rates of nutrient influx, I_n in both the crops showed various degrees of correlation with age and rate of shoot growth. In corn, I_n for ions reached a maximum at 25 days growth; whereas, in alfalfa, I_n reached maximum at 30 days of growth. The differences in influx rates for different ions in the two species are probably due to the

 0190-4167/86/0911-1391$3.50/0

difference in development of shoot and root parameters and shoot demand for the ions.

INTRODUCTION

In the soil system the nutrient uptake is the result of interactions between the rate of absorption by roots and soil factors that determine the rate of flux of nutrient to the soil-root interface. The pattern of nutrient absorption varies with age, with the plant species and with nutrient (3,4,5,10,11,15, 17,19,20,21,22,27,29,35,36,37,38,39). Plant species and cultivars differ widely in their response to the concentration of nutrients in the growth medium (3,5,6,7,8,9,11,16,20,21,29,33, 36). The differences in nutrient accumulation by plants often are assumed to be dependent on root morphological parameters such as length, surface area, dry weight, volume (4,5,6,8,18, 28,32,34) and physiological conditions of the plant (13,24).

In the present investigation, nutrient solution cultures were used to study differences in nutrient uptake characteristics of alfalfa and corn. A nutrient culture system keeps the supply of ions to roots at a constant rate and also it eliminates the influence of soil on the process of ion transfer to root surface. When the ion concentration in the nutrient solution exceeds a certain minimum value the availability of ions at the root surface does not limit rate of uptake (2,12,26).

Often the comparison of cultivars for nutrient uptake were done either by evaluating the percentage of elemental composition in shoot material or by total uptake per unit dry matter. In plant nutrition studies it is essential to consider rate of nutrient flux per unit root length (or weight) to characterize efficiency of root systems to meeting plant nutrient demand.

In the view of the above considerations a solution culture experiment with corn and alfalfa was conducted to study the relationship between plant growth (or age) and: (1) shoot and root development, (2) plant induced pH changes in root environment and (3) variations in the percentage, total uptake and net influx rate of ions.

MATERIALS AND METHODS

Corn (*Zea mays* var. SX111-F5-159696-32C5) and alfalfa (*Medicago sativa* L. var. Iroquois) seeds were germinated on moistened filter paper immersed in aerated tap water. At 5 days, seedlings were suspended in 2 liter plastic containers of aerated nutrient solution to grow until harvesting. Five corn and 10 alfalfa plants were maintained per pot. The composition of the nutrient solution was 2.5 mM Ca, 1 mM Mg, 1 mM K, 3 mM N, 0.5 mM P, 2.0 mM S, 46 μM B, 0.8 μM Zn, 0.3 μM Cu, 0.5 μM Mo, 9mM Mn, and 75 μM Fe as Fe-DTPA (diethylenetriamine pentaacetic acid). Solution pH was initially adjusted to 5.0. The solution was changed every 24 hours. After every pH determination, solution was renewed and pH was adjusted to 5.0. The experiment was carried out in the greenhouse during the months of June and July. Plant growth pots were suspended in a fiberglass drum, in which water was circulated to keep the nutrient solution temperature at 25±2°C. Two pots of each plant species were harvested at five day intervals. Root weight and shoot weight were measured and root length was determined by Tennants method (30). Plant samples were wet ashed by digesting in H_2SO_4 and H_2O_2. P was determined by the Murphy and Riley (23) procedure, K and Na by flame emission, and Ca and Mg by atomic absorption. Nitrogen was determined by the Thomas *et al*. (31) procedure.

The relative root growth rate, kr, was calculated as follows:

$$kr = [\ln L_2 - \ln L_1] / [T_2 - T_1] \qquad [1]$$

where L refers to root length, (cm/plant) and T refers to time in seconds. The subsript 1 refers to the initial harvest value (5 days) and 2 for subsequent harvests.

The relative shoot growth rate, ks, was determined using the relation given in equation 1 substituting shoot weight (g/plant) for root length (cm/plant).

The nutrient influx rate, I_n (pmoles $cm^{-1}sec^{-1}$) was worked out as follows:

$$I_n = [(U_2-U_1)/(T_2-T_1)]\ [(\ln L_2-\ln L_1)/L_2-L_1)] \qquad [2]$$

where U refers to given ion quantity in a whole plant (mmoles/plant).

RESULTS AND DISCUSSION

Plant Induced pH Changes

The pH of the nutrient medium measured before its daily renewal is shown in Fig. 1. Both crops, with age, increased the pH of the nutrient solution. Modification of solution pH is attributed to the release of OH^- ions by plant roots. Riley and Barber (25) have reported that the pH in the rhizosphere is lowered by the absorption of NH_4^+ and raised by the absorption of NO_3^-. In the present study both the crops received N in the form of $Ca(NO_3)_2$ and absorption of NO_3^- by roots eventually might have resulted in release of OH^- and HCO_3^- by plant roots. Such a release by roots is essential to maintain cellular pH and electrical neutrality of the root system. Rise in pH with corn was very pronounced at all the stages of its growth; however, after 30 days of growth, the change in nutrient medium pH with alfalfa was similar to that of corn. This difference between the two species might be attributable to the difference in their demand for anions particularly nitrate ions. Corn is a heavy nitrogen feeder. After 10 days growth, corn demand for nitrogen per plant was 22 times higher than that of alfalfa. Corn roots must be releasing a much higher proportion of OH^- and HCO_3^- ions than alfalfa roots. There is tendency of corn plant to raise the pH towards neutral range even at an early stages of its growth. The ability of corn roots to increase soil pH, even at early stages of growth, should be taken into account when interpreting experimental results.

Shoot and Root Growth Parameters

Changes in shoot and root growth parameters with plant age of alfalfa and corn are shown in Table 1. The linear correlation values for growth parameters vs growth stages are listed in Table 2.

Both plant weight and root length in alfalfa and corn increased exponentially with time which commonly occurs when

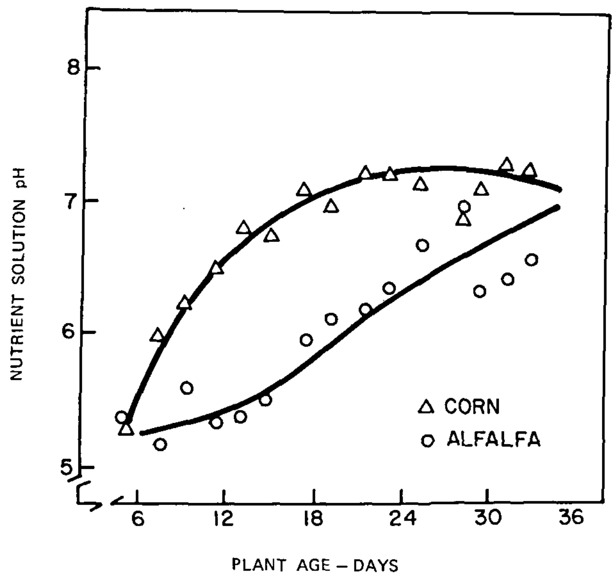

Fig. 1. pH changes in the nutrient media during the growth of alfalfa and corn.

the plants are grown with uniform environmental conditions. Even though both crop species were grown under identical environmental conditions, root and shoot parameters differed due to differences in the interaction of plant genetic factors with the environment. Because alfalfa is a slow growing plant it is expected to have low demand for nutrients.

The shoot:root ratio (S:R) differ between species and within a particular species, the S:R value may vary with age, stage of morphological development, and kind of growing environments. In alfalfa there was very little change in S:R with increasing plant age which shows that root growth is synchronized with the morphological stages of the shoot; however, in corn the S:R ratio increased with plant age. The increased S:R ratio can be attributed to greater carbohydrate utilization by the shoot at the expense of the roots.

Measurement of relative growth rate during plant growth provided a good general index of the intrinsic physiology of the

TABLE 1

The relation between growth stages and shoot and root development in alfalfa and corn plants

Crop	Plant Age at Harvest	Total Plant Weight	Shoot / Root	Root Length	kr	ks
	days	g/plant	S:R	m/plant	---$sec^{-1}X10^{6}$---	
Alfalfa	10	0.003c*	6.88a	0.09c	2.05c	1.60d
	15	0.006c	6.75a	0.37bc	2.63b	1.86cd
	20	0.016c	7.00a	2.11bc	3.07a	2.00bc
	25	0.061c	7.01a	3.72bc	2.65b	2.31ab
	30	0.200b	6.13a	6.53b	2.38bc	2.39a
	35	0.543a	7.45a	18.04a	2.37bc	2.38a
Corn	10	0.248e	1.70d	33.78c	10.00a	5.19a
	15	0.620de	3.10d	44.99c	5.33b	3.84b
	20	1.530d	5.36c	64.29c	3.83c	3.34c
	25	4.295c	7.36b	123.25b	3.25d	3.13d
	30	10.036b	5.37c	259.39a	2.94e	2.88e
	35	16.309a	8.58a	304.65a	2.51f	2.61f

*Means with the same letter are not significantly different at the 0.05 level by DMR test. Analysis for each crop done seperately.

TABLE 2

Correlation coefficient, R values for growth parameters in alfalfa and corn plants.

Variables	Correlation coefficient, R: Alfalfa	Corn
Age vs. Shoot wt.	0.84*	0.92**
Age vs. Root wt.	0.86*	0.91*
Age vs. Plant wt.	0.84*	0.93**
Age vs. S:R	0.12NS	0.90*
Age vs. Root length	0.87*	0.94**
Age vs. kr	0.07NS	-0.86*
Age vs. ks	0.96**	-0.91*

* Significant at 5% level.
** Significant at 1% level.
NS Not significant.

plant. The kr and ks were calculated for the period of each successive harvest by taking growth at 5 days as initial. In alfalfa the kr did not change much with time (r^2 = 0.01). The ks for alfalfa increased with plant age (r^2 = 0.92). In corn total plant weight (r^2 = 0.86), root length (r^2 = 0.88) and S:R (r^2 = 0.81) increased; whereas, kr (r^2 = 0.74) and ks (r^2 = 0.83) decreased with plant age. Expression of root and shoot parameters in the two species were consistantly different.

Concentration of elements in shoot

The elemental concentration changes in alfalfa and corn with age of growth are shown in Table 3.

Variation in nutrient concentration of the shoot is observed with both the crops. Such variation may reflect differences in utilization of absorbed ions, efficiency of ion uptake or both. Variation in nutrient concentration in a given genotype may occur even where total uptake remains the same. Such differences are due not only to genetically controlled internal factors, but also to variation in root morphological and anatomical features (14,32,33). Throughout the growth phase, alfalfa exhibited higher concentrations of N, K, Na and Ca than corn; whereas at all growth stages corn had slightly higher percentages of P. In its early stage of growth, alfalfa had slightly higher Mg concentration than corn, but with further growth its Mg concentration declined. With the exception of Ca in alfalfa and Mg and Na in corn, the concentration of all the other elements under consideration decreased with age. Because in alfalfa a total dry matter production was lower than that of corn, there was a much lower nutrient dilution effect on plant composition.

Nutrient Uptake

Plant age and its influence on nutrient uptake is given in Table 4. In both crops, uptake of all the elements increased with age. At each stage of growth the species differed in their content of nutrients and at all the growth stages, alfalfa absorbed less nutrients per plant than corn. Significant differ-

TABLE 3

Plant growth stages and percentage of ions in alfalfa and corn shoots

Crop	Plant Age at Harvest	Element N	P	K	Na	Ca	Mg
	days	% in shoot					
Alfalfa	10	3.84ab*	1.09a	4.43a	0.42a	0.63c	0.21a
	15	3.69b	1.00ab	5.22a	0.12b	0.99b	0.21a
	20	4.25a	0.99ab	4.84a	0.07c	1.27a	0.21a
	25	3.95ab	0.81b	3.44b	0.04d	1.32a	0.13b
	30	3.21c	0.61c	3.31b	0.02d	1.22a	0.09b
	35	2.97c	0.58c	3.23b	0.02d	1.13ab	0.09b
Corn	10	3.47b	1.16a	3.55a	0.02b	0.60b	0.14b
	15	3.95a	1.19a	3.46a	0.03a	0.75a	0.19ab
	20	3.49b	1.07ab	3.48a	0.03a	0.66ab	0.22ab
	25	2.69c	0.94b	3.23c	0.02b	0.59b	0.26a
	30	1.83d	0.65c	1.98d	0.02b	0.37c	0.21ab
	35	2.12d	0.55c	1.57e	0.02b	0.39c	0.20ab

*Means with the same letter are not significantly different at the 0.05 level by DMR test. Analysis for each crop done seperately.

TABLE 4

Influence of plant age on nutrient uptake by alfalfa and corn plants

Crop	Plant Age at Harvest	Uptake N	P	K	Na $X10^2$	Ca $X10^2$	Mg $X10^2$
	days	mmoles/plant					
Alfalfa	10	0.01c*	0.001b	0.001c	0.001b	0.01c	0.01c
	15	0.02c	0.002b	0.004c	0.005b	0.06c	0.02c
	20	0.04c	0.006b	0.020c	0.026b	0.58c	0.17c
	25	0.16bc	0.014b	0.053c	0.137b	2.06bc	0.30bc
	30	0.34b	0.038b	0.172b	0.623a	5.90b	0.78b
	35	1.13a	0.106a	0.454a	0.810a	14.57a	2.07a
Corn	10	0.22e	0.003d	0.080e	0.100d	1.0d	0.50c
	15	1.48de	0.160d	0.480e	0.720cd	9.5d	3.80c
	20	2.91d	0.438cd	1.339d	3.600cd	22.5cd	12.50c
	25	7.76c	1.162c	3.610c	7.900c	56.5bc	41.50bc
	30	12.56b	1.995b	4.950b	17.100b	87.5b	83.50ab
	35	23.59a	2.749a	6.770a	28.600a	153.5a	124.50a

*Means with the same letter are not significantly different at the 0.05 level by DMR test.

ences in nutrient uptake were noted for growth stages beyond 25 and 20 days for alfalfa and corn, respectively. With its greater dry matter accumulation capacity corn is able to take up more nutrients than alfalfa. Corn plant at 35 days of growth had absorbed 21, 26, 15, 35, 11 and 60 times more N, P, K, Na, Ca, and Mg respectively per plant than alfalfa of similar age.

Nutrient Influx Rate, I_n.

Plant age or stage of development has an effect on the nutrient demand and rate of ion influx at the root surface. The rate of nutrient absorption by the root frequently determines the growth rate of the crop. The relation between age and net influx rates, I_n, for different ions are shown in Table 5. Nutrient influx rate in corn increased with age; whereas, in alfalfa increase in nutrient influx rate was very much evident with growth beyond 15 days. Warncke and Barber (37) observed that rates of N, P, K, Ca, and Mg uptake rate in nutrient solution culture by corn plants increased rapidly with plant age until the silking stage. The rate then decreased as the plant went from the vegetative to the reproductive stage of growth. In alfalfa, at 10 days growth, there was higher I_n values recorded for N, P, K, and Mg than at 15 days growth. High rates of influx in early stages would indicate that the rate of supply of these nutrients through the soil to the roots needs to be higher when the plants are young than when they are older. With the exception of N, the I_n values for all the ions for alfalfa reached a maximum at 30 days growth and declined thereafter. The I_n values for P, K, Ca, and Mg in corn reached maximum at 25 days growth and declined thereafter. In a field study, Mengel and Barber (22) working with corn recorded a decrease in I_n values from 12 to 0.1 pmoles cm^{-1} of root length sec^{-1} as plant age increased from 20 to 70 days. The differences in influx rates between two crops for different ions also may be attributable to the possible differences that might exist in ion influx kinetics at the root surfaces. Jung and Barber (19) with corn and Edwards and Barber (15) with soybeans attributed the difference in P influx with plant age to variation in the maximum influx rate, I_{max}, and the Michaelis-Menten constant Km. In another study, Edwards and Barber (14) with corn plants showed that I_{max} for N

TABLE 5

The relationship between plant age and net influx rate of ions into roots of alfalfa and corn plants

Crop	Plant Age at Harvest	Net influx Rate, I_n N	P	K	Na	Ca	Mg
	days	pmoles cm^{-1} sec^{-1}					
Alfalfa	10	3.62a*	0.150a	0.42ab	0.004d	0.05b	0.019abc
	15	1.56b	0.040d	0.28b	0.004d	0.05b	0.014c
	20	0.61c	0.060d	0.29b	0.006c	0.06b	0.018bc
	25	1.15b	0.110c	0.39ab	0.010b	0.15a	0.021abc
	30	1.27b	0.140a	0.65a	0.023a	0.22a	0.029a
	35	1.50b	0.140a	0.61a	0.011b	0.20a	0.028ab
Corn	10	0.65c	0.008d	0.23c	0.003b	0.04c	0.014c
	15	1.37b	0.191c	0.57b	0.009b	0.12ab	0.045bc
	20	1.74ab	0.262ab	0.79a	0.021a	0.14ab	0.074ab
	25	1.86a	0.308a	0.96a	0.021a	0.15a	0.110a
	30	1.54ab	0.232bc	0.57b	0.019a	0.10b	0.090a
	35	1.95a	0.225bc	0.60b	0.024a	0.13ab	0.110a

*Means with same letter are not significantly different at the 0.05 level by DMR test. Analysis for each crop done separately.

TABLE 6

Correlation coefficient, R values for I_n against plant age and ks.

Variables	Correlation coefficient, R Alfalfa	Corn
Age vs. I_n, N	-0.56	0.80
Age vs. I_n, P	0.35	0.63
Age vs. I_n, K	0.73	0.45
Age vs. I_n, Na	0.72	0.87*
Age vs. I_n, Ca	0.92*	0.54
Age vs. I_n, Mg	0.84*	0.88*
ks vs. I_n, N	-0.68	-0.94*
ks vs. I_n, P	0.23	-0.83*
ks vs. I_n, K	0.63	-0.68
ks vs. I_n, Na	0.77	-0.93*
ks vs. I_n, Ca	0.91*	-0.80
ks vs. I_n, Mg	0.76	-0.92*

*Significant at 5% level.

reached a maximum in plants 18 to 21 days old and then decreased approximately exponentially with plant age.

The correlation coefficient values for age vs I_n for the ions under consideration and ks vs I_n, are listed in Table 6. The I_n values for different ions in corn showed a high degree of correlation with age. In corn, a negative correlation existed between ks and I_n for all the ions under consideration. In alfalfa, with the exception of N, all the I_n values showed a positive correlation with ks.

ACKNOWLEDGEMENTS

The author thanks Dr. M. H. Miller of the University of Guelph for providing necessary facilities and equipment to carry out this research. The excellant technical assistance of Alex Burachynsky is greatly appreciated. The author thanks M. R. Evans for the statistical analysis of the data. Helpful suggestions of Drs. K. D. Ritchey and E. Elkhatib in final draft of this manuscript is appreciated.

REFERENCES

1. Present address: USDA-ARS, Appalachian Soil and Water Conservation Research Laboratory, P.O. Box 867, Airport Road, Beckley, WV 25802-0867.

2. Alberda, T. H. 1965. The influence of temperature, ligth intensity and nitrate concentration of dry-matter production and chemical composition of Lolium perenne L. Neth. J. Agric. Sci. 13:335-360.

3. Asher, C. J., and J. F. Loneragan. 1967. Response of plants to phosphate concentration in solution culture: I. Growth and phosphate content. Soil Sci. 103:225-233.

4. Baligar, V. C. 1985. Absorption kinetics of Ca, Mg, Na, and P by intact corn and onion roots. J. Plant Nut. 8:543-554.

5. Baliagr, V. C. 1985. Postassium uptake by plants, as characterized by root density, species, and K/Rb ratio. Plant and Soil. 85:43-53.

6. Baligar, V. C. and S. A. Barber. 1978. Use of K/Rb ratio to characterize potassium uptake by plant roots growing in soil. Soil Sci. Soc. Am. J. 42:575-579.

7. Baligar, V. C. and S. A. Barber. 1978. Potassium uptake by onion roots characterized by potassium/rubidium ratio. Soil Sci. Soc. Am. J. 42:618-622.

8. Baligar, V. C. and S. A. Barber. 1979. Genotypic differences of corn for ion uptake. Agron. J. 71:870-876.

9. Barber, S. A. 1974. Properties of the plant root that influences fertilizer practices. Proc. 7th Int. Colloq. Plant Anal. and Fert. Prob. 1:25-33.

10. Bates, T. E. 1971. Factors affecting critical nutrient concentrations in plants and their evaluation: A review. Soil Sci. 112:116-130.

11. Christie, E. K. and J. Moorby. 1975. Physiological responses of semiarid grasses. I. The influence of phosphorus suppy on growth and phosphorus absorption. Aust. J. Agric. Res. 26:423-436.

12. Clement, C. R., M. J. Hooper, R. J. Canaway, and L. H. P. Jones. 1974. A system for measuring the uptake of ions by plants from flowing solutions of controlled composition. J. Exp. Bot. 25:81-99.

13. Drew, M. C., P. H. Nye, and L. V. Vaidyanathan. 1969. The supply of nutrient ions by diffusion to plant roots in soil. I. Absorption of potassium by cylindrical roots of onion and leak. Plant and Soil. 30:252-270.

14. Edwards, J. H., and S. A. Barber. 1976a. Nitrogen uptake characteristics of corn roots at low N concentration as influenced by plant age. Agron. J. 68:17-19.

15. Edwards, J. H. and S. A. Barber. 1976b. Phosphorus uptake rate of soybean roots as influenced by plant age, root trimming and solution P concentrations. Agron. J. 68:973-975.

16. Epstein, E. and R. L. Jefferies. 1964. The genetic basis of selective ion transport in plants. Ann. Rev. Plant Physiol. 15:169-184.

17. Fageria, N. K. 1976. Effect of P, Ca, and Mg concentrations in solution culture on growth and uptake of these ions by rice. Agron. J. 68:726-732.

18. Hackett, C. 1969. A study of the root system of barley. II. Relationships between root dimensions and nutrient uptake. New Phytol. 68:1023-1030.

19. Jungk, A., and S. A. Barber. 1975. Plant age and the phosphorus uptake characteristics of trimmed and untrimmed corn root systems. Plant and Soil. 42:227-239.

20. Loneragan, J. F. and C. J. Asher. 1967. Response of plants to phosphate concentration in solution culture: II. Rate of phosphate absorption and its relation to growth. Soil Sci. 103:311-318.

21. McLachlan, K. D. 1976. Comparative phosphorus responses in plants to a range of available phosphorus situations. Aust. J. Agric. Res. 27:323-341.

22. Mengel, D. B. and S. A. Barber. 1974. Rate of nutrient uptake per unit of corn root under field conditions. Agron. J. 66:399-402.

23. Murphy, J. and J. P. Riley. 1962. A modified single solution method for determination of phosphate in natural waters. Anal. Chem. Acta. 27:31-36.

24. Pitman, M. G. 1972. Uptake and transport of ions in barley seedlings. III. Correlation between transport to the shoot and relative growth rate. Aust. J. Biol. Sci. 25:905-919.

25. Riley, D. and S. A. Barber. 1971. Effect of ammonium and nitrate fertilization on phosphorus uptake as related to root induced pH changes at the root-soil interface. Soil Sci. Soc. Amer. Proc. 35:301-306.

26. Reisenauer, H. M. 1969. A technique for growing plants at controlled levels of all nutrients. Soil Sci. 108:350-353.

27. Russell, R. S., E. W. Russell, and P. G. Marais. 1958. Factors affecting the ability of plants to absorbe phosphate from soil. II. A comparison of the ability of different species to absorb labile soil phosphate. J. Soil Sci. 9:101-108.

28. Russell, R. S. and J. Sanderson. 1967. Nutrient uptake by different parts of the intact roots of plants. J. Exp. Bot. 18:491-508.

29. Temple-Smith, M. G., and R. C. Menary. 1977. Growth and phosphate absorption in lettuce and cabbage plants in dilute solution culture. Aust. J. Plant Physiol. 4:505-513.

30. Tennant, D. 1975. A test of modified line intersect method of estimating root length. J. of Ecol. 63:995-1001.

31. Thomas, R. L., R. W. Sheard, and J. R. Moyer. 1967. Comparison of conventional and automated procedures for nitrogen, phosphorus and potassium analyses of plant materials using a single digestion. Agron. J. 59:240-243.

32. Veen, B. W. 1977. The uptake of potassium nitrate, water, and oxygen by a maize root system in relation to its size. J. Expt. Bot. 28:1389-1398.

33. Vose, P. B. 1963. Varietal differences in plant nutrition. Herb. Abstr. 33:1-13.

34. Vose, P. B. 1981. Potential use of induced mutants in crop plant physiology studies. pp. 159-181. In induced Mutations: A Tool in Plant Breeding. International Atomic Energy Agency, Vienna.

35. Vose, P. B. 1982. Effect of genetic factors on nutritional requirements of plants. pp. 67-107. In: Contemporary Bases for Crop Breeding, Eds. P. B. Vose and S. G. Blixt. Pergamon Press, New York, NY.

36. Warncke, D. D. and S. A. Barber. 1974a. Nitrate uptake effectiveness of four plant species. J. Environ. Quality. 3:28-30.

37. Warncke, D. D. and S. A. Barber. 1974b. Root development and nutrient uptake by corn grown in solution culture. Agron. J. 66:514-516.

38. Wild, A., V. Skarlou, C. R. Clement, and R. W. Snaydon. 1974. Comparison of potassium uptake by four plant species grown in sand and in flowing solution culture. J. Appl. Ecol. 11:801-812.

39. Woodhouse, P. J., A. Wild, and C. R. Clement. 1978. Rate of uptake of potassium by three crop species in relation to growth. J. Expt. Bot. 29:885-894.